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Stable D8-branes and tachyon condensation in type 0 open string theory

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Abstract: We consider non-BPS D8 (and D7) branes in type 0 open string theory and describe under which circumstances these branes are stable. We find stable non-BPS D7 and D8 in type 0 with and without D9-branes in the background. By extending the descent relations between D-branes to type 0 theories, the non-BPS D8-brane is considered as the result of a tachyon condensation of a D9 anti-D9 pair in type 0. We study the condensation of the open string tachyons in type 0 with generic gauge groups giving rise to different configurations involving non-BPS D8-branes and discuss the stability in each case. The results agree with the topological analysis of the vacuum manifold of the tachyon potential for each case.

Keywords: D-branes, Brane Dynamics in Gauge Theories, Solitons Monopoles and Instantons.

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Contents

1. Introduction

In the past year there has been a tremendous increase in our knowledge about non-BPS states and non-BPS branes in string theory [1, 2, 3]. We have learned that only under certain circumstances these branes can be stable. This fact has been used in order to extend the duality checks to the non-BPS part of spectrum of the string theories [2]–[7]. These developments find a natural implementation in the context of non-supersymmetric strings, where the lack of spacetime supersymmetry forces one to find other stability conditions for the solitons of the theory, which allow one to establish duality relations to some extent [8]–[13]. Moreover, there are indications that non-supersymmetric strings might find their place in the unification picture of M-theory [12]. It is then natural to try to check these dualities by means of stable non-BPS states in the non-supersymmetric theory.[1] Thus it is interesting

[1] Since we do not have spacetime supersymmetry, non-BPS means in this context that there is no fixed relation between the mass and the charge.

to find stable non-BPS states and in particular stable non-BPS D-branes in non-supersymmetric string theories. Progress in this context has been reported in [13], where a stable D-particle was constructed in type 0 open string theory with gauge group SO(32) $\times$ SO(32).

In this paper we describe the non-BPS D7 and D8 branes of type 0 open string theory and in particular, we discuss under which circumstances they are stable. We use the fact that in type 0 theory the background of D9-branes is not completely determined by the tadpole cancellation, and study the different possibilities. This makes possible to find that, although non-BPS D7 and D8 branes are not stable in type I [14], they can be stable in type 0. Non-BPS Dp-branes appear in general as a kink solution in the tachyon potential of a D$(p+1)$-brane anti-D$(p+1)$-brane pair [6, 15]. Similarly we consider these D8-branes in type 0 as the result of tachyon condensation of the D9 anti-D9 pairs in type 0 open string theory. More generally, we analyze the mechanism of tachyon condensation of the D9 anti-D9 pairs giving rise to non-BPS D8-branes for generic type 0 backgrounds with symmetries SO$(n) \times$ SO$(m) \times$ SO$(n) \times$ SO(m), SO$(n) \times$ SO$(n) \times \mathbb{Z}_2$, SO$(n) \times$ SO(n) and $\mathbb{Z}_2 \times \mathbb{Z}_2$. We study the stability in terms of the resulting brane configuration and using topological arguments; and show that both results agree.

This article is organized as follows. In section 2 we describe the type 0 open string theory first considered in [16]. We briefly review the tadpole cancellation with D9-branes, which can give rise to groups of the form SO$(N) \times$ SO$(32-N) \times$ SO$(N) \times$ SO$(32-N)$. We also show how to obtain the same group structure from an orbifold of type I. In section 3 we show that a non-BPS D8_+ (D8_-) brane is stable if (1) there are only D9_- and anti-D9_- (D9_+ and anti-D9_+) branes in the background or when (2) there are no D9-branes at all in the background. These results are completely analogous for the non-BPS D7-brane. Finally, in section 4 we describe the condensation of the open string tachyons between the D9-branes and anti-D9-branes in type 0 open string theory for different generic situations.

2. Type 0 open string theory

Type 0B (0A) theory is obtained as an orbifold of type IIB (IIA) by the spacetime fermion number operator $(-1)^{F_s}$ [17]. The spectrum of the type 0B (0A) theory and of most of their open descendants contains double the number of R-R fields with respect to the type II case. We denote these two fields as:

$$(R+, R\pm) \Rightarrow C^{(p+1)}\,, \qquad (R-, R\mp) \Rightarrow \bar{C}^{(p+1)}\,, \tag{2.1}$$

where the upper signs[2] correspond to the type 0B with p odd, and the lower signs

[2]These signs refer to the worldsheet fermion numbers of the left and right moving sectors, i.e. the eigenvalues of $(-1)^{F_L}$ and $(-1)^{F_R}$, respectively.

correspond to type 0A with p even. We consider the combinations [18]:

$$C_{\pm}^{(p+1)} = \frac{1}{\sqrt{2}} \left(C^{(p+1)} \pm \bar{C}^{(p+1)} \right) . \tag{2.2}$$

Consequently, we have two types of Dp-branes for each p, that we denote as Dp_+ and Dp_-, which carry one unit of charge under $C_+^{(p+1)}$ and $C_-^{(p+1)}$, respectively. The relation between these charges and the charges of the R-R fields in (2.1) is given by

$$q_{\pm} = \frac{1}{2}(q \pm \bar{q}) . \tag{2.3}$$

Type 0 theory can be obtained as an orientifold of type 0B by Ω [16], or as an orbifold by $(-1)^{F_s}$ of type I [8]. The projection of type I by $(-1)^{F_s}$ eliminates all the fermions from the spectrum. The (massless) untwisted sector is given by the metric, the dilaton, and a R-R 2-form $C^{(2)}$, in the sector $(R+, R+)$. The twisted sector introduces a tachyon $(NS-, NS-)$ and a second R-R 2-form $\bar{C}^{(2)}$ in the sector $(R-, R-)$. The orbifold $(-1)^{F_s}$ has the same effect as a diagonal GSO projection. Accordingly, the contribution of the Klein bottle to the one-loop vacuum amplitude only gives rise to a NS-NS massless tadpole in the tree channel, hence the Orientifold fixed plane of type 0 carries no R-R charge.[3] The NS-NS tadpole does not render the theory necessarily inconsistent, hence in principle we do not need to introduce D9-branes, so we could do without an open-string sector in the theory. The NS-NS can in fact be removed by a Fischler-Susskind mechanism [19], which introduces a spacetime dependent coupling.

2.1 Tadpole cancellation in type 0

The NS-NS tadpole of type 0 can also be canceled by adding D9-branes, which introduce an open sector in the theory. Since only the cylinder diagram contributes to a R-R massless tadpole, this must be canceled by the D9-branes themselves, hence we have to take an equal number of D9-branes and anti D9-branes. The cancellation of the NS-NS tadpole tells us that the number of branes to be introduced is $N = 32$:

$$\mathcal{A}^{NSNS} = -V_{10} \int_0^{\infty} \frac{d\ell}{2} (8\pi^2\alpha') \left(\frac{1}{2}(2N)^2 \mathrm{e}^{2\pi\ell} + 16(N-32)^2 \right) . \tag{2.4}$$

The exponentially divergent term is a tachyon tadpole, which is expected in a theory with a tachyon in the closed string spectrum. Thus type 0 string theory without tadpoles can have a gauge group SO(32) $\times$ SO(32).

On the other hand, we know that type 0B contains two types of Dp-branes for each p odd. This implies that we also have two types of D9-branes in the type 0

[3]The Klein-Bottle contribution in type 0 is the double of the type I case, so one could consider one Orientifold and one anti-Orientifold [22] in type 0 [23]. However, since they carry no R-R charge, they cannot be distinguished in type 0.

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theory [8, 12]. Thus regarding the type 0 theory as a type 0B orientifold, there are different possible combinations of D9-branes which cancel the tadpoles. The generic case is a system of N D9$_+$ branes and $32-N$ D9$_-$ branes, with their respective antibranes. This configuration originates the gauge group $\mathrm{SO}(N)\times\mathrm{SO}(32-N)\times\mathrm{SO}(N)\times\mathrm{SO}(32-N)$, and the R-R and NS-NS massless tadpoles vanish. Moreover, the tachyon tadpole is slightly changed:

$$\mathcal{A}^{NSNS} = -V_{10}\int_0^\infty d\ell\,(8\pi^2\alpha')\,(32-2N)^2\,\mathrm{e}^{2\pi\ell}\,, \tag{2.5}$$

and vanishes for $N=16$. This is the situation where we have 16 D9$_+$ and 16 D9$_-$ branes and their respective antibranes, which is equivalent to 16 bound states of the form D9$_\pm$ plus the corresponding antibranes. The fact that the tachyon tadpole vanishes[4] in this specific configuration is consistent with the fact that the potential between the D9$_\pm$ bound states is proportional to the potential between type I D9-branes. One concludes that from the point of view of a type 0B orientifold, type 0 without tadpoles can have in general $\mathrm{SO}(N)\times\mathrm{SO}(32-N)\times\mathrm{SO}(N)\times\mathrm{SO}(32-N)$ symmetry.

2.2 Type 0 as an orbifold of type I

The generic configuration of D9-branes with gauge group $\mathrm{SO}(N)\times\mathrm{SO}(32-N)\times\mathrm{SO}(N)\times\mathrm{SO}(32-N)$ can also be made consistent with the orbifold construction of type 0 from type I.[5] Consider the gauge transformation

$$\mathcal{I} = \begin{pmatrix} -\mathbb{1}_N & 0 \\ 0 & \mathbb{1}_{32-N} \end{pmatrix}, \tag{2.6}$$

which acts on the Chan-Paton factors of the open string states as

$$|\ldots\rangle\otimes\Lambda \longrightarrow |\ldots\rangle\otimes\mathcal{I}\Lambda\mathcal{I}^{-1}\,. \tag{2.7}$$

The orbifold[6] of type I by $(-1)^{F_s}\cdot\mathcal{I}$ then yields the type 0 theory with gauge group $\mathrm{SO}(N)\times\mathrm{SO}(32-N)\times\mathrm{SO}(N)\times\mathrm{SO}(32-N)$. This construction goes schematically as follows. The group element $\mathcal{I}$ makes a natural division of the 32 D9-branes of type I into two sets, one with N branes and the other one with $32-N$ branes. Accordingly, the Chan-Paton factors for open strings can be divided as

$$\Lambda = \begin{pmatrix} A & B \\ C & D \end{pmatrix}, \tag{2.8}$$

where A is an $N\times N$ matrix associated to the N D9-branes of the first set, and D is a $(32-N)\times(32-N)$ matrix associated to the other $32-N$ D9-branes. B and C

[4]Although the closed string tachyon does not appear in the cylinder amplitude for $N=16$, it does appear in the torus amplitude.

[5]This extents the result of [8], where only the $\mathrm{SO}(32)\times\mathrm{SO}(32)$ case was obtained as an orbifold of type I.

[6]This type of projection was used previously in [20] to connect the D3-brane of type IIB with the D3$_\pm$ bound state of type 0B.

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are the Chan-Paton factors for the open strings stretching from one of the N branes of the first set and another one from the second set with $32-N$ branes. Orbifolding by $(-1)^{F_s}\cdot\mathcal{I}$ we eliminate the fermions in the open strings which begin and end on branes of the same set, and the bosons of the open strings with each end in a brane of either set. The gauge group SO(32) is thus broken down to $\mathrm{SO}(N)\times\mathrm{SO}(32-N)$ and we are left with massless fermions in the $(\mathbf{N},\mathbf{32}-\mathbf{N})$ representation. This implies that the 32 D9-branes become N D9-branes of one type and $32-N$ D9-branes of the other one, either $\mathrm{D9}_+$ or $\mathrm{D9}_-$.

The anti D9-branes can be considered as coming from the twisted sector of the orbifold $(-1)^{F_s}\cdot\mathcal{I}$. Implementing the orbifold projection on this twisted sector we find N anti D9-branes of one type and $32-N$ of the other type. Moreover, tadpole cancellation[7] imposes that the N anti D9-branes must be of the same type as the N D9-branes of the untwisted sector, and similarly for the other $32-N$ D9-branes. The operation $\mathcal{I}$ does not act on the closed string spectrum. Thus after orbifolding type I by $(-1)^{F_s}\cdot\mathcal{I}$ we obtain the same closed spectrum as before. Finally, we obtain the type 0 theory with the group $\mathrm{SO}(N)\times\mathrm{SO}(32-N)\times\mathrm{SO}(N)\times\mathrm{SO}(32-N)$, containing both $\mathrm{D9}_+$ and $\mathrm{D9}_-$ branes.

$$\begin{tikzcd}
\textbf{type IIB} \arrow[r, "(-1)^{F_s}"] \arrow[d, "\Omega"'] & \textbf{type 0B} \arrow[d, "\Omega"] \\
\textbf{type I} \arrow[r, "(-1)^{F_s} I"] & \textbf{type 0}
\end{tikzcd}$$

Figure 1: Type 0 theory. This graphic shows how to construct type 0 theory from type 0B and type I, with a gauge group of the form $\mathrm{SO}(N)\times\mathrm{SO}(32-N)\times\mathrm{SO}(N)\times\mathrm{SO}(32-N)$. The operator $\mathcal{I}$ determines N in the construction from type I. This choice corresponds in the orientifold case to a certain gauge freedom we have in order to choose the types of branes canceling the tadpole.

Finally, we would like to emphasize that the introduction of the D9-branes is completely arbitrary, since there is no R-R tadpole to cancel and the NS-NS tadpole is harmless and can be treated with a Fischler-Susskind mechanism [19]. Accordingly, we can consider a generic type 0 theory with n $\mathrm{D9}_+$ branes and m $\mathrm{D9}_-$ branes, and the corresponding antibranes. The gauge group is $\mathrm{SO}(n)\times\mathrm{SO}(m)\times\mathrm{SO}(n)\times\mathrm{SO}(m)$ and there is a NS-NS tadpole unless $n+m=32$. In particular, we can consider type 0 with no D9-branes at all, hence the open sector would be absent. From now on we will consider these more generic backgrounds for type 0. The transition from one case to the other with less branes can be seen as produced by the annihilation of D9 anti-D9 pairs into the vacuum, where the open string tachyon condenses restoring the vacuum. In section 4 we will propose an alternative tachyon condensation for which the D9 anti-D9 pair gives rise to a non-BPS D8-brane. We proceed now with the description of this non-BPS D8-brane.

[7] One might think that there is an ambiguity in the choice of type of brane in the twisted sector. However, in a configuration with N $\mathrm{D9}_+$ branes, $32-N$ $\mathrm{D9}_-$ branes, $32-N$ anti $\mathrm{D9}_+$ branes and N anti $\mathrm{D9}_-$ branes, the tachyon tadpole vanishes for any N, but the R-R tadpole would only vanish for $N=16$.

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3. Stable D8-brane in type 0

Using the descent relations between D-branes in type II theories [21, 2], one can construct a non-BPS D($2p$)-brane in type IIB theory. This can be obtained either from a D($2p+1$) anti-D($2p+1$) pair in type IIB, or from a D($2p$) anti-D($2p$) pair of type IIA. We can extend these relations to type 0A/0B theories. For instance, in a D$(2p+1)_+$ anti-D$(2p+1)_+$ pair in type 0B there is a non-BPS D$(2p)_+$ brane associated to the tachyonic kink solution. This construction goes through like in type II, except for the R-sector which is absent. This non-BPS D$(2p)_+$ brane can also be constructed from a D$(2p)_+$ anti-D$(2p)_+$ pair of type 0A. In order to obtain this, we argue that the orbifold projection of type 0A (0B) by $(-1)^{F_L^s}$ yields type 0B (0A), where $(-1)^{F_L^s}$ is the spacetime fermion-number of the left-movers and acts with a minus sign on the R-R sectors. In this way we can start with a D8_+ anti-D8_+ pair in type 0A and by projecting with $(-1)^{F_L^s}$ we obtain a non-BPS D8_+-brane in type 0B, or else, we can construct the non-BPS D8_+ brane as a kink solution of the tachyon potential in a D9_+ anti-D9_+ pair in type 0B. The low-energy field content on this non-BPS D8_+ brane in type 0B is the same as for the non-BPS D8-brane of type IIB but without fermions: an U(1) vector, a transversal scalar and a tachyon. This can also be obtained from the non-BPS D8-brane in type IIB by projecting with the orbifold $(-1)^{F_s}$.

Notice that we can choose between two types of branes, either Dp_+ or Dp_-. We can distinguish a non-BPS D8_+ from a non-BPS D8_- in type 0B at low energies by the sign of the coupling to the closed string tachyon. In order to see this we compare the cylinder amplitude between two non-BPS D8_+ branes

$$\mathcal{A}_{\mathrm{D}8_+-\mathrm{D}8_+} = V_9 \int_0^\infty \frac{dt}{2t} (8\pi^2\alpha' t)^{-\frac{9}{2}}\, \mathrm{e}^{-\frac{Y^2 t}{2\pi\alpha'}}\, \frac{f_3^8(\mathrm{e}^{-\pi t})}{f_1^8(\mathrm{e}^{-\pi t})}\,, \tag{3.1}$$

with the amplitude between a non-BPS D8_+ and a non-BPS D8_-:

$$\mathcal{A}_{\mathrm{D}8_+-\mathrm{D}8_-} = -V_9 \int_0^\infty \frac{dt}{2t} (8\pi^2\alpha' t)^{-\frac{9}{2}}\, \mathrm{e}^{-\frac{Y^2 t}{2\pi\alpha'}}\, \frac{f_2^8(\mathrm{e}^{-\pi t})}{f_1^8(\mathrm{e}^{-\pi t})}\,. \tag{3.2}$$

We factorize the cylinder in the closed string channel, expanding for small t. We find

$$\frac{f_3^8(\mathrm{e}^{-\pi t})}{f_1^8(\mathrm{e}^{-\pi t})} \sim t^4\left(\mathrm{e}^{\pi/t}+8\right), \qquad -\frac{f_2^8(\mathrm{e}^{-\pi t})}{f_1^8(\mathrm{e}^{-\pi t})} \sim t^4\left(-\mathrm{e}^{\pi/t}+8\right). \tag{3.3}$$

Thus we can conclude that they couple with a different sign to the closed string tachyon. Notice also that the bound state D$8_\pm$ has a cylinder amplitude proportional to that of a non-BPS D8-brane in type IIB.

In order to obtain the D8_+ brane of type 0 theory we must consider the projection by Ω in the D8_+ brane of type 0B. From [14] we know that the action of Ω on the 8-8 strings is the following. For the $(-1)^F$ NS even part we find

$$\Omega\, \psi^i_{-1/2}|0\rangle = -\psi^i_{-1/2}|0\rangle\,, \tag{3.4}$$

for the NN directions, and

$$\Omega\,\psi^9_{-1/2}|0\rangle = \psi^9_{-1/2}|0\rangle\,, \tag{3.5}$$

for the DD direction. Thus the U(1) gauge field is projected out and only the massless transversal scalar survives. In the $(-1)^F$ NS odd part we have

$$\Omega|0\rangle = -|0\rangle\,, \tag{3.6}$$

so the tachyon is projected out, and this $D8_+$ brane is in principle stable.

One can also consider a system of n $D8_+$-branes in type 0. However, the worldvolume theory will be given by a non-abelian vector field and a tachyon in the adjoint representation of SO(n), and a transversal scalar in the symmetric representation of SO(n). Thus a system of n $D8_+$ ($D8_-$) branes is in general not stable in type 0 string theory.

We find that a single $D8_+$ brane in type 0 is in principle stable, and only contains a scalar in its worldvolume theory. In order to complete the analysis we must consider the open strings which eventually appear stretching between the D8-brane and the D9-branes. There are several possibilities that we describe next and which are summarized in table 1.

3.1 Stable D8-brane in type 0 with D9-branes

In type 0 theory with D9-branes in the background there are also 8-9 open strings, stretching between the $D8_+$ brane and the D9 and anti-D9 branes. Consider the case of a $D8_+$ brane in the background of 32 $D9_+$ branes and 32 anti-$D9_+$ branes. There are then 64 tachyons in the spectrum of the 8-9 strings which appear in the NS-sector, for which

$$L_0 - \frac{3}{8} = 0 \tag{3.7}$$

on the physical states. On the other hand, if we have a $D8_+$ brane in the background of 32 $D9_-$ branes and 32 anti-$D9_-$ branes, there appear no tachyons in the 8-9 strings since these only contain a R-sector. Thus we find that a single $D8_+$ ($D8_-$) brane is stable in type 0 if there are only $D9_-$ ($D9_+$) branes in the background. If we disregard the NS-NS tadpole, we can have any gauge group of the form SO$(n)\times$ SO(n).

Notice that although in type I the D8-brane is not stable [14], it can be stable in type 0. In fact, this can also be derived from the non-BPS D8-brane of type I. Consider the construction of type 0 from type I with the orbifold $(-1)^{F_s}\cdot\mathcal{I}$ as explained in section 2, where $\mathcal{I}$ is taken to be of the form (2.6). There are tachyons in the NS-sector of the 8-9 strings in type I, which can be represented by

$$|0\rangle\otimes\Lambda^a\,,\qquad a=1,\ldots,32\,, \tag{3.8}$$

Stable Branes	Type 0 Background	Gauge Symmetry
$D7_+$, $D8_+$ $D7_-$, $D8_-$ $D7_\pm$, $D8_\pm$	No D9-branes	–
$D7_+$, $D8_+$	n $D9_-$ and n anti-$D9_-$	$SO(n) \times SO(n)$
$D7_-$, $D8_-$	n $D9_+$ and n anti-$D9_+$	$SO(n) \times SO(n)$

Table 1: Stable D7 and D8 branes in type 0. In this table we show for which cases a single D7 or D8 brane can be stable in type 0. The bound states $D7_\pm$ and $D8_\pm$ are also considered. We also indicate the gauge group when we have n D9 anti-D9 pairs, with n arbitrary.

where Λ^a denotes the Chan-Paton factor of the 8-9 strings.[8] The orbifold symmetry has a natural action on these Chan-Paton factors:

$$|0\rangle \otimes \Lambda^a \longrightarrow |0\rangle \otimes \mathcal{I}^a{}_b \Lambda^b \,, \tag{3.9}$$

which can be used to project out N of the tachyons. This also keeps $32-N$ tachyons, coming from the strings stretching between the D8-brane and $32 - N$ D9-branes.[9] In the twisted sector one has 32 anti-D9-branes, which give rise to 32 extra tachyons in the 8-9 sector. Finally, one performs again the projection onto invariant states under the transformation (3.9). As a result we obtain $2(32 - N)$ tachyons coming from the $D8_+$-$D9_+$ and $D8_+$-anti-$D9_+$ sectors, or similarly, from the $D8_-$-$D9_-$ and $D8_-$-anti-$D9_-$ sectors. In particular, using this procedure we obtain a stable D8-brane in type 0 with $SO(32) \times SO(32)$ gauge group for the case $\mathcal{I} = -\mathbb{1}_{32}$. Thus we find again that a non-BPS $D8_+$ ($D8_-$) branes is stable if there are only $D9_-$ ($D9_+$) branes in the background.

3.2 Stable D8-brane in type 0 without D9-branes

We can make the choice of not introducing any D9-brane at all in type 0. The resulting theory has no open string sector, contains a tachyon in the closed string sector and a massless NS-NS tadpole. In this situation there is no 8-9 open string sector, so that a single $D8_+$ ($D8_-$) brane is stable. Moreover, since the spectrum of the open strings stretched between a $D8_+$ and a $D8_-$ is in the R-sector (see (3.2)), we can also consider the bound state $D8_\pm$, which is also stable.

We can perform a similar analysis for a non-BPS D7-brane in type 0, using the results of [14]. We find a stable non-BPS $D7_+$ ($D7_-$) brane in type 0 for the same cases as for the $D8_+$ ($D8_-$) brane. We summarize these results in table 1.

[8] Since the theory is unoriented this sector contains in fact a certain combination of 8-9 and 9-8 strings.

[9] Recall that these $32-N$ D9-branes are of a different type from the other N D9-branes. In fact, this projection also keeps the R-sector only in the strings stretched between the D8 and the first N D9-branes.

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4. Tachyon condensation in type 0

A generic background of type 0 contains an equal number of D9-branes and anti-D9-branes. This is in fact a natural setting for the study of tachyon condensation. If the D9 and anti-D9 branes annihilate into the vacuum, we are left with the O9 and the anti-O9 planes, which originate a negative tree-level cosmological constant [23]. We can consider instead a tachyon condensation for which a D9 anti-D9 pair gives rise to a non-BPS D8-brane. In this section we consider this type of condensation and discuss the stability of the resulting configurations. We start with the most general case of type 0 with symmetry $\mathrm{SO}(n) \times \mathrm{SO}(m) \times \mathrm{SO}(n) \times \mathrm{SO}(m)$. We also consider other cases included in this one, which are obtained by letting some of the D9 anti-D9 pairs to condense into the vacuum.

4.1 $\mathrm{SO}(n) \times \mathrm{SO}(m) \times \mathrm{SO}(n) \times \mathrm{SO}(m)$ symmetry

Let us consider type 0 with gauge group $\mathrm{SO}(n) \times \mathrm{SO}(m) \times \mathrm{SO}(n) \times \mathrm{SO}(m)$, originated by n $\mathrm{D9}_+$ and m $\mathrm{D9}_-$ branes, and the corresponding antibranes. There is moreover an extra $\mathbb{Z}_2$ symmetry corresponding to the exchange $\mathrm{D9}_+ \leftrightarrow \mathrm{D9}_-$. In this case there are tachyons in the $(\mathbf{n}, \mathbf{1}, \mathbf{n}, \mathbf{1})$ and $(\mathbf{1}, \mathbf{m}, \mathbf{1}, \mathbf{m})$ representations. Consider the condensation of all the D9 anti-D9 pairs of a given type, for instance $\mathrm{D9}_-$, into D8-branes. We obtain m non-BPS $\mathrm{D8}_-$ branes in the background of n $\mathrm{D9}_+$ anti-$\mathrm{D9}_+$ pairs. Although we find no tachyons in the 8-9 strings, there are tachyons in the 8-8 strings as shown in section 3, so the system of n D8-branes is not stable. A similar result is obtained if we let the system condense to m non-BPS $\mathrm{D8}_-$ branes plus n non-BPS $\mathrm{D8}_+$ branes.

We can compare this result with the analysis of the symmetries of the tachyon potential, in a similar fashion as in [24]. The tachyon potential has a $\mathrm{SO}(n) \times \mathrm{SO}(m) \times \mathrm{SO}(n) \times \mathrm{SO}(m)$ symmetry, hence the vacuum manifold, $S^{n-1} \times S^{m-1} \times S^{n-1} \times S^{m-1}$, is connected. Thus there are no stable kink solutions to this potential. The system is then expected to decay into the vacuum.

4.2 $\mathrm{SO}(n) \times \mathrm{SO}(n) \times \mathbb{Z}_2$ symmetry

In the above configuration, we can consider the condensation of k, $k < m$, $\mathrm{D9}_-$ anti-$\mathrm{D9}_-$ pairs into $\mathrm{D8}_-$ branes and $m-k$ pairs into the vacuum. The result is a set of k non-BPS $\mathrm{D8}_-$ branes in the background of n $\mathrm{D9}_+$ anti-$\mathrm{D9}_+$ pairs. For $k > 1$ the D8-branes are not stable since there are tachyons in the 8-8 sector. Moreover, the background is not stable since there are tachyons in the 9-9 sector. If the n $\mathrm{D9}_+$ anti-$\mathrm{D9}_+$ pairs decay into the vacuum, the result is then a set of k non-BPS $\mathrm{D8}_-$ branes in type 0 without D9-branes. According to the results of section 3 this is only stable for $k = 1$.

We compare now with the analysis of the symmetries of the tachyon potential. The condensation of k $\mathrm{D9}_-$ anti-$\mathrm{D9}_-$ pairs into $\mathrm{D8}_-$ branes and $m-k$ pairs into the vacuum requires that some of the components of the $(\mathbf{1}, \mathbf{m}, \mathbf{1}, \mathbf{m})$ tachyon must condense independently. In order for this to be possible the group associated to the $D9_-$ branes, the symmetry $SO(m) \times SO(m)$ must be broken down to $SO(m-k) \times SO(m-k) \times SO(k) \times SO(k)$. The part $SO(m-k) \times SO(m-k)$ is associated to the D9-branes that condense into the vacuum, so we need not to consider it any longer. The relevant symmetry group in order to seek for kink solutions is $SO(n) \times SO(k) \times SO(n) \times SO(k)$, originated by k $D9_-$ anti-$D9_-$ pairs , which we plan to condense into $D8_-$ branes; and by n $D9_+$ anti-$D9_+$ pairs that we leave untouched in the background. For $k > 1$ the vacuum manifold associated to the tachyon potential is again connected and we find no stable kinks.

If $k = 1$, we have n $D9_+$ anti-$D9_+$ pairs and just one $D9_-$ anti-$D9_-$ pair.[10] The symmetry of the tachyon potential is $SO(n) \times SO(n) \times \mathbb{Z}_2$ and the vacuum manifold corresponds to two discrete copies of $S^{n-1} \times S^{n-1}$. This is not connected and accepts a topological stable kink solution corresponding[11] to a stable non-BPS $D8_-$ brane in the background of n $D9_+$ anti-$D9_+$ pairs. These n pairs are not stable due to the tachyons in the 9-9 sector, so that they can decay into the vacuum and we are left with a single stable non-BPS $D8_-$.

4.3 $SO(n) \times SO(n)$ symmetry

If all the D9 anti-D9 pairs of a given type decay into the vacuum, we are left with type 0 with a gauge group of the form $SO(n) \times SO(n)$. This symmetry is originated by n $D9_+$ (or $D9_-$) branes and the corresponding n antibranes. This theory has a tachyon in the $(\mathbf{n}, \mathbf{n})$ representation. The analysis of this case is similar to the one above.

If we consider the condensation of k pairs, $n \geq k > 1$, we obtain k non-BPS $D8_+$ ($D8_-$) branes in the background of $n-k$ $D9_+$ anti-$D9_+$ ($D9_-$ anti-$D9_-$) pairs. This is not stable since there are tachyons in the 8-8 strings. If the $n-k$ D9 anti-D9 pairs do not decay into the vacuum, there are moreover tachyons in the 8-9 and 9-9 strings. The relevant tachyon potential has $SO(k) \times SO(k)$ symmetry, so that the minimum describes a vacuum manifold of the form $S^{k-1} \times S^{k-1}$. This manifold is connected so there is no topological stable kink. The case $k = 1$ is included in the discussion below.

4.4 $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry

A special case is when we let all the D9 anti-D9 pairs condense into the vacuum except for a pair of each type, i.e. we are left with one $D9_+$ anti-$D9_+$ pair and one $D9_-$ anti-$D9_-$ pair. The symmetry $SO(n) \times SO(m) \times SO(n) \times SO(m)$ is then broken

[10] We do not consider the rest of the $D9_-$ anti-$D9_-$ pairs which have condensed into the vacuum.

[11] One can also consider the condensation of a higher tachyonic mode of a single D9 anti-D9 pair. This will give rise in general to $n+1$ kinks and n $(n+1)$ anti-kinks, which will correspond to $2n+1$ $(2n+2)$ non-BPS D8-branes. I thank A. Sen for drawing my attention to this possibility.

down to $\mathbb{Z}_2 \times \mathbb{Z}_2$. We have two tachyon fields with a $\mathbb{Z}_2$ symmetry each. Moreover, there is one extra $\mathbb{Z}_2$ symmetry corresponding to the exchange $D9_+ \leftrightarrow D9_-$. Let us analyze the possible kink solutions in this potential. One possibility is that one tachyon condenses into a kink solution and the other condenses into the vacuum. This gives us two possible kinks, which are indistinguishable because of the extra $\mathbb{Z}_2$ symmetry. The result is a stable non-BPS D8 brane, either $D8_+$ or $D8_-$, in type 0 without D9-branes. One can of course leave one of the D9 anti-D9 pairs intact. The symmetry of the potential is then $\mathbb{Z}_2$ and we obtain, after tachyon condensation, a non-BPS $D8_+$ ($D8_-$) brane in type 0 with a $D9_-$ anti-$D9_-$ ($D9_+$ anti-$D9_+$) pair in the background, which is also stable.

Another possibility is when both tachyons condense into a kink. Notice that both tachyon fields have dependence on the same compact direction X along the D9-branes. The position of the zero of the first tachyon kink along the X-axis is free to be chosen by reparametrisation invariance. However, the relative position of the zero of the second tachyon is not. Consequently we obtain a 1-parameter family of kink-pairs, where the parameter indicates the relative distance between the zeroes of the two kinks. On the other hand, the X-axis becomes the direction transverse to the non-BPS D8-branes after tachyon condensation [6]. Thus the distance-parameter indicates the relative distance between the non-BPS $D8_+$ and the non-BPS $D8_-$ after tachyon condensation. This means that in the procedure of tachyon condensation we obtain a stable non-BPS $D8_+$ - $D8_-$ pair with a relative separation distance. In particular, when the zeros of both kinks coincide, we obtain the stable bound state $D8_\pm$.

5. Conclusions

We have found stable non-BPS D7 and D8 branes in type 0. We have made use of the fact that the background of D9-branes in type 0 is not completely determined by the tadpole cancellation, and that we have the freedom of choosing between two types of D9-branes. Moreover, disregarding the NS-NS tadpole, which can be removed by other means, we can have any number of D9 anti-D9 pairs in the background. The results are summarized in table 1.

The open string tachyon in the D9 anti-D9 pair can condense to give rise to the non-BPS D8-brane described in this paper. We have analyzed the tachyon condensation in type 0 for several generic configurations of D9-branes, and found that only when there is a $\mathbb{Z}_2$ symmetry involved the condensation yields a stable configuration. This corresponds to having only one D9 anti-D9 pair of at least one type, either $D9_+$ or $D9_-$. For the particular case of the $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry there is also a freedom to separate the resulting non-BPS branes in the procedure of tachyon condensation.

We notice that in type 0 the NS-NS tadpole can be eliminated either by a Fischler-Susskind mechanism, or by adding D9 and anti-D9 branes. The Fischler-

Susskind mechanism introduces a spacetime-dependent metric and dilaton. On the other hand, the D9 anti-D9 pairs can give rise to non-BPS D8-branes after tachyon condensation. In general, a background with D8-branes has associated a metric and a dilaton with non-trivial dependence on the spacetime [25]. It would be interesting to investigate further the background of type 0 in the presence of these non-BPS D8 branes and see whether there is any relation with a Fischler-Susskind mechanism in type 0.

Finally, type 0 with gauge group $SO(32) \times SO(32)$ was conjectured to be S-dual to the compactification of the 26-dimensional bosonic string on the SO(32) weight lattice [8]. It would be interesting to find out whether this duality can be extended to more generic type 0 backgrounds, like those described in this paper. Moreover, it would be very interesting to see to which states correspond the stable non-BPS D7 and D8 branes in the dual theory.

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